TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Tests were made in the N.A.C.A. gust tunnel to determine the effectiveness of a long-period dynamically overbalanced flap in reducing airplane accelerations due to atmospheric gusts. For two gust shapes, one gust velocity, one forward velocity, and one wing loading, a series of flights was made with the flap locked and was then repeated with the flap free to operate. The records obtained were evaluated by routine methods.

The results indicate that the flap reduced the maximum acceleration increment 39 percent for a severe gust with a representative gust gradient distance of 8 chord lengths and that, for an extreme gust shape (a sharp-edge gust), the reduction was only 3 percent. The results also indicate that the flap tended to reduce the longitudinal stability of the airplane. Computations made of the effectiveness and the action of the flap were in good agreement with the experimental results.

INTRODUCTION

From time to time, various methods of reducing the acceleration due to gusts encountered by an airplane in flight have been suggested. Among these methods are spring-mounting the fuselage to the wings and the use of automatic flaps controlled by the motion of the air or the airplane. Although interest has been shown in these suggestions for improving the riding comfort of airplanes, the effectiveness of such devices is difficult to compute and to investigate experimentally.

The N.A.C.A. gust tunnel now offers a convenient means of investigating gust-alleviating devices under known conditions. The present investigation was undertaken to determine the effectiveness of a long-period dynamically overbalanced flap in reducing the normal accelerations due to known gusts.

Tests were made in the N.A.C.A. gust tunnel during the spring of 1938 on an arbitrary airplane model for two gust shapes.

APPARATUS

The gust tunnel and the auxiliary equipment have been described in reference 1. The gust shapes used during the investigation are shown in figure 1.

The airplane model (fig. 2) was equipped with a rectangular wing. The general dimensions and characteristics of the model are given in table I. The characteristics of an airplane 13.4 times as large have been included in table I for purposes of comparison.

The airplane model was conventional in all respects except that it was equipped with a dynamically overbalanced flap. Figure 3 shows the details of the flap mechanism. The flap was attached to the wing by means of 12 pivot and socket bearings to keep the friction a minimum. At each hinge (fig. 3), an arm 1.2 inches long, which supported a 0.27-ounce weight at its extremity, was attached to the flap. The overbalance caused in this manner was counteracted by a coiled spring at each hinge. Small disks (fig. 3) were used to provide damping, which could be varied by inserting oil of suitable viscosity between the disks.

The effective period of the flap could not be experimentally determined owing to the nature of the mechanism. An approximate calculation, however, indicated an effective period of 1.25 seconds, which is quite large when compared with the normal value for the time from zero to maximum acceleration increment (0.03 to 0.14 second). The relative lengths of the times indicate that the mass attached to the 1.2-inch arm would tend to maintain a fixed path in space when the model was vertically displaced. The flap displacement would therefore be a direct function of the vertical-displacement increment of the airplane model for moderate flap displacements and for the periods of time considered here.

As all computations were based on a rigid wing, the wing was made as rigid as possible. In order to obtain a measure of the wing rigidity, the static-wing deflection curve and the natural period were experimentally determined. The wing-deflection curve for a load factor of 1.16 (fig. 4) was obtained for a uniform span loading. The natural wing period, determined with the model elastically supported, is included in table I.

In addition to the regular apparatus and instruments used in all tests at the gust tunnel (reference 1), a high-speed motion-picture camera was used to record the flap motion during part of two flights. The pictures were taken at about 2,000 frames per second and covered about 2 to 3 feet of the traverse of the gust tunnel by the model.

TESTS

The test procedure consisted in flying the model over the gust tunnel under identical conditions except for the flap, which was either locked or free. The tests were made for two gust gradient distances of one and eight chord lengths, one forward velocity, one gust velocity, and one value of wing loading. The velocities and the wing loading are included in table I; the gust shapes are shown in figure 1. Five flights were made for each condition to obtain mean values of the acceleration increment.

In addition to the main series of tests, a few flights were made to obtain high-speed motion pictures of the flap motion during part of the traverse of a gust with a gradient distance of eight chord lengths.

RESULTS

The records obtained during the tests were evaluated to give histories of events during entry into and traverse of the gust. Sample histories of uncorrected results for repeat flights for each test condition are shown in figures 5 and 6.

The maximum acceleration increments for all runs were corrected to the nominal values of forward velocity and gust velocity given in table I. The resulting values are shown in figure 7 for the flap-locked and the flap-free conditions as a function of the gust gradient distance.

The flap effectiveness, defined as the percentage reduction in maximum acceleration increment due to the flap, was computed for each gradient distance from the data of figures 7(a) and 7(b) and is shown in figure 8.

The high-speed motion pictures of the flap motion were evaluated to obtain the flap displacement as a function of the distance penetrated into the gust. The results are given in figure 9.

PRECISION

The measured quantities are estimated to be accurate within the following limits for any run:

Acceleration increment - - - - $\pm 0.1g$

Forward velocity - - - - - - - - - - ± 1.0 foot per second

Gust velocity - - - - - - - - - - - ± 0.1 foot per second

Pitch-displacement increment - - $\pm 0.2^{\circ}$

Vertical-displacement increment - ± 0.01 foot

Flap displacement - - - - - - - - - $\pm 2^{\circ}$

An approximate calculation based on the natural period (table I) and the wing-deflection curve of figure 4 indicates an error in acceleration increment due to wing flexibility of not more than 2.5 percent. This error is felt to be well within the accuracy of the other measurements and will therefore be neglected.

DISCUSSION

As previously mentioned, the flap mechanism was so designed that the flap displacement, δ, was a direct function of the vertical-displacement increment of the model for moderate flap displacements. As a result of this method of operation, the flap should be relatively ineffective for sharp gusts but its effectiveness should tend to increase as the gradient distance increases. Inspection of figure 8 substantiates this reasoning, the results indicating a flap effectiveness of only 3 percent for a sharp-edge gust as compared with about 38 to 40 percent for a gust with a gradient distance of eight chord lengths. In the practical application of this mechanism, the small reduction in acceleration in a sharp-edge gust can be ignored because the sharp-edge gust represents an extreme gust shape that is indicated by unpublished data to be seldom encountered in flight.

Attempts to calculate the effectiveness of the flap mechanism by use of the unsteady lift functions given in reference 2 for a flapped wing indicated that the theoretical flap constant (rate of change of effective angle of attack with flap displacement), developed for a sealed flap, would give unsatisfactory results. The flap used in this investigation was unsealed, and the data on flapped wings given in reference 3 indicate that the flap constant is a function of the flap displacement. Figure 10 gives the variation of the flap constant k with flap displacement for a 10-percent-chord flap such as used on the present model. In view of this result, the computations were repeated with the varying flap constant of figure 10.

The analysis was made with the following assumptions:

1. The acceleration increment is a linear function of the distance penetrated into a linear gradient gust.

2. The flap displacement varies directly with the vertical-displacement increment of the model; that is, the mass attached to the flap maintains a fixed path in space when the model is displaced.

3. The pitch of the airplane model is negligible to peak acceleration.

4. Whether the flap is free or locked, the maximum acceleration increment will occur at the same distance from the start of the gust (equations (3) and (4) of reference 4).

The equation for Δn, the maximum acceleration increment, is:

$$\Delta n = \frac{dC_L}{d\alpha}\frac{Sq}{W}\frac{1}{V}\int_0^{s_1} C_{L_g}(s_1 - s)\frac{dU}{ds}\,ds$$

$$- \frac{dC_L}{d\alpha}\frac{Sq}{W}\frac{K_1}{V}\int_0^{s_1} C_{L_\alpha}(s_1 - s)\,\Delta n(s)\,ds$$

$$- \frac{dC_L}{d\alpha}\frac{Sq}{W}K_2\int_0^{s_1} C_{L_\alpha}(s_1 - s)\frac{d(k\delta)}{ds}\,ds \qquad (1)$$

where

Δn is acceleration increment at point of maximum gust velocity for a linear gradient gust.

$\frac{dC_L}{d\alpha}$, slope of wing-lift curve per radian.

S, wing area.

q, dynamic pressure.

W, airplane weight.

V, forward velocity (assumed constant).

U, gust velocity at any point.

s, distance airplane has penetrated into gust, chord lengths.

s_1, gradient distance, chord lengths.

C_{L_g}, unsteady-lift function for an airfoil penetrating a sharp-edge gust.

C_{L_α}, unsteady-lift function for a sudden change of angle of attack, $C_{L_\alpha} = 1 - \frac{2}{4 + 2s}$ (derived from equation (1a), reference 5).

δ, flap displacement.

k, flap constant (fig. 10). For the purpose of this analysis, $k = 0.0617\ \delta^{-2/3}$.

$K_1, K_2, K_3 \ldots K_n$, constants.

Inspection of equation (1) discloses that the acceleration increment is made up of three components: that due to the action of the gust, that due to the vertical velocity of the airplane, and that due to the motion of the flap. The first term can be written as $\frac{dC_L}{d\alpha} \frac{SqU_1}{WV} \frac{A}{s_1}$ for the gradient gust or as $\frac{dC_L}{d\alpha} \frac{SqU_1}{WV} \eta_o$ for a sharp-edge gust, where U_1 is the gust velocity at s_1 and where A and η_o are the functions of s_1 given in reference 4. This term represents the acceleration of the airplane when the lag in lift is taken into account but the vertical motion of the airplane is neglected. For convenience, it will be designated Δn_o. The last two terms depend on the final value of the acceleration and are not so easily obtained.

Since the acceleration increment is assumed to be a linear function of time or of s, the second term of equation (1) can be reduced to

$$\frac{dC_L}{d\alpha} \frac{Sqc}{WV^2} \frac{\Delta n}{s_1} \int_0^{s_1} \left[1 - \frac{2}{4 + 2(s_1 - s)}\right] s\,ds$$

$$= \frac{dC_L}{d\alpha} \frac{Sqc}{WV^2} \frac{\Delta n}{s_1} \left[\frac{s_1^2}{2} + \left(s_1 + \frac{4 + 2s_1}{2} \log_e \frac{4}{4 + 2s_1}\right)\right]$$

$$= K_3(\Delta n) \quad \text{for a particular value of } s_1.$$

This equation indicates that the component due to the vertical motion of the airplane is a function of the impressed acceleration and the gradient distance s_1.

The third term of equation (1) contains no direct expression for Δn but is dependent on Δn, since δ is a function of the double integral of the acceleration increment. When δ is computed from the vertical displacement of the model, it is found that

$$\delta = K_4 \frac{\Delta n}{s_1} s^3$$

so that

$$k\delta = K_5 \left(\frac{\Delta n}{s_1}\right)^{1/3} s$$

and

$$\frac{d(k\delta)}{ds} = K_5 \left(\frac{\Delta n}{s_1}\right)^{1/3}$$

When $K_5 \left(\frac{\Delta n}{s_1}\right)^{1/3}$ is substituted for $\frac{d(k\delta)}{ds}$ in the third term of equation (1), the following expression is obtained:

$$\frac{dC_L}{d\alpha} \frac{Sq}{W} K_6 \left(\frac{\Delta n}{s_1}\right)^{1/3} \int_0^{s_1} \left[1 - \frac{2}{4 + 2(s_1 - s)}\right] ds$$

$$= \frac{dC_L}{d\alpha} \frac{Sq}{W} K_6 \left(\frac{\Delta n}{s_1}\right)^{1/3} \left(s_1 + \log_e \frac{4}{4 + 2s_1}\right)$$

or the third component is $K_7 (\Delta n)^{1/3}$ for a particular value of s_1.

When the expressions obtained for the three terms of equation (1) are introduced into the original equation, the solution for a particular value of s_1 is obtained by a process of iteration, as:

$$\Delta n_1 = \Delta n_0 - K_3 (\Delta n_0) - K_7 (\Delta n_0)^{1/3}$$

$$\Delta n_n = \Delta n_0 - K_3 \left[\Delta n_{(n-1)}\right] - K_7 \left[\Delta n_{(n-1)}\right]^{1/3}$$

The iteration process converges quite rapidly and is easy to carry out if the last two terms are plotted as functions of Δn for different values of s_1.

In the present case, the computation was made for several values of the gust gradient distance and for several gust velocities. The resulting curves, given in figures 8 and 11, indicate that the flap effectiveness increases as the gradient distance increases and as the gust velocity decreases. The experimental values from the gust-tunnel tests, shown in figure 8, indicate excellent agreement between calculation and experiment. It appears, therefore, that the flap would be more effective in smoothing out the small bumps than the large ones. The computed flap displacements have been included in figure 9. The results indicate excellent agreement with the experimental data in spite of the assumption that the sine of the angle was equal to the angle. The excellent agreement, however, may be due to compensating errors in the assumptions used in the development of the equations.

The effect of the flap on the longitudinal stability of the airplane is adverse, as would be expected, in that it reduces the pitch of the airplane in the gust. This reduction is shown by the pitch-increment curves of figures 5 and 6. A comparison of the curves for the free flap and the locked flap shows a marked decrease in the negative pitch. This decrease is particularly noticeable when figures 5(a) and 5(b) are compared.

It might be well to point out that a device which tends to maintain the wing lift at a constant value will also tend to reduce the maneuverability of the airplane. Any acceleration imposed on the airplane to change its flight path will be modified by the influence of the flap unless provision is made for the pilot to override the flap action when using the controls.

CONCLUSIONS

For the airplane model tested, the results indicate that the flap reduced the maximum acceleration increment 39 percent for a severe gust with a representative gust gradient distance of eight chord lengths and, for an extreme gust shape (a sharp-edge gust), the reduction was only 3 percent. The results also indicated that the flap tended to reduce the longitudinal stability of the airplane. Computations made of the effectiveness and the action of the flap were in good agreement with the experimental results.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 8, 1939.

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4. Rhode, Richard V.: Gust Loads on Airplanes. S.A.E. Trans., vol. 32, 1937, pp. 81-88.

5. Garrick, I. E.: On Some Reciprocal Relations in the Theory of Nonstationary Flows. T.R. No. 629, N.A.C.A., 1938.

TABLE I

Characteristics of Airplane Model

	Model	Hypothetical airplane
Weight, lb.	1.62	3910
Wing area, sq. ft.	1.65	297
Wing loading, lb. per sq. ft.	0.98	13.2
Span, ft.	3.09	41.4
Mean geometric chord, ft.	0.535	7.2
Center of gravity, percent M.A.C.	25	25
Fundamental wing period, sec.	0.0294	0.1076
Moment of inertia, mk_Y^2, slug-ft.^{2}	0.00786	3420
Gust velocity, f.p.s.	6.9	25.2
Forward velocity, f.p.s.	63.5	232
Span of flap, percent wing span	100	100
Chord of flap, percent wing chord	10	10

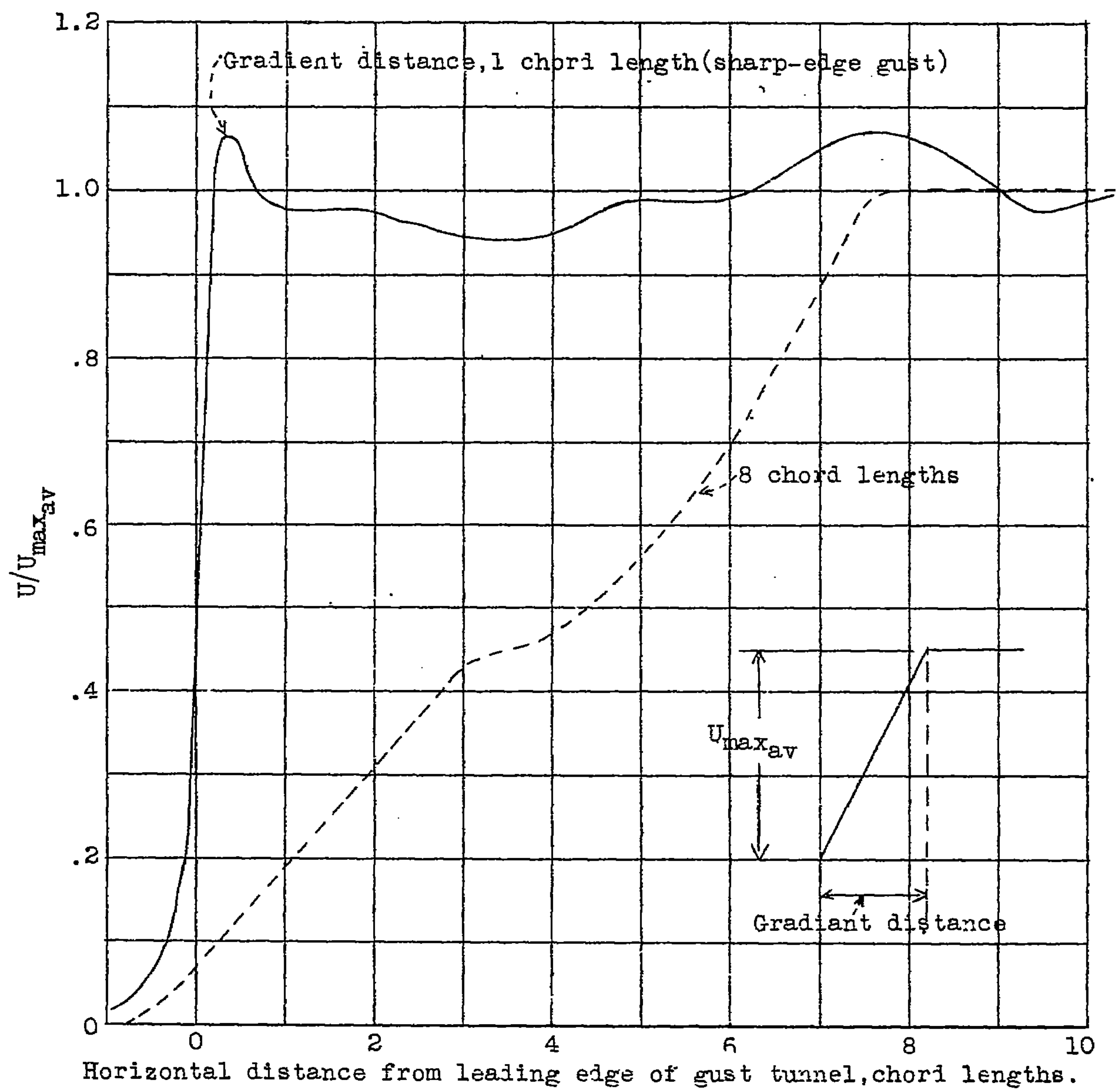


Figure 1.- Velocity distribution through jet.

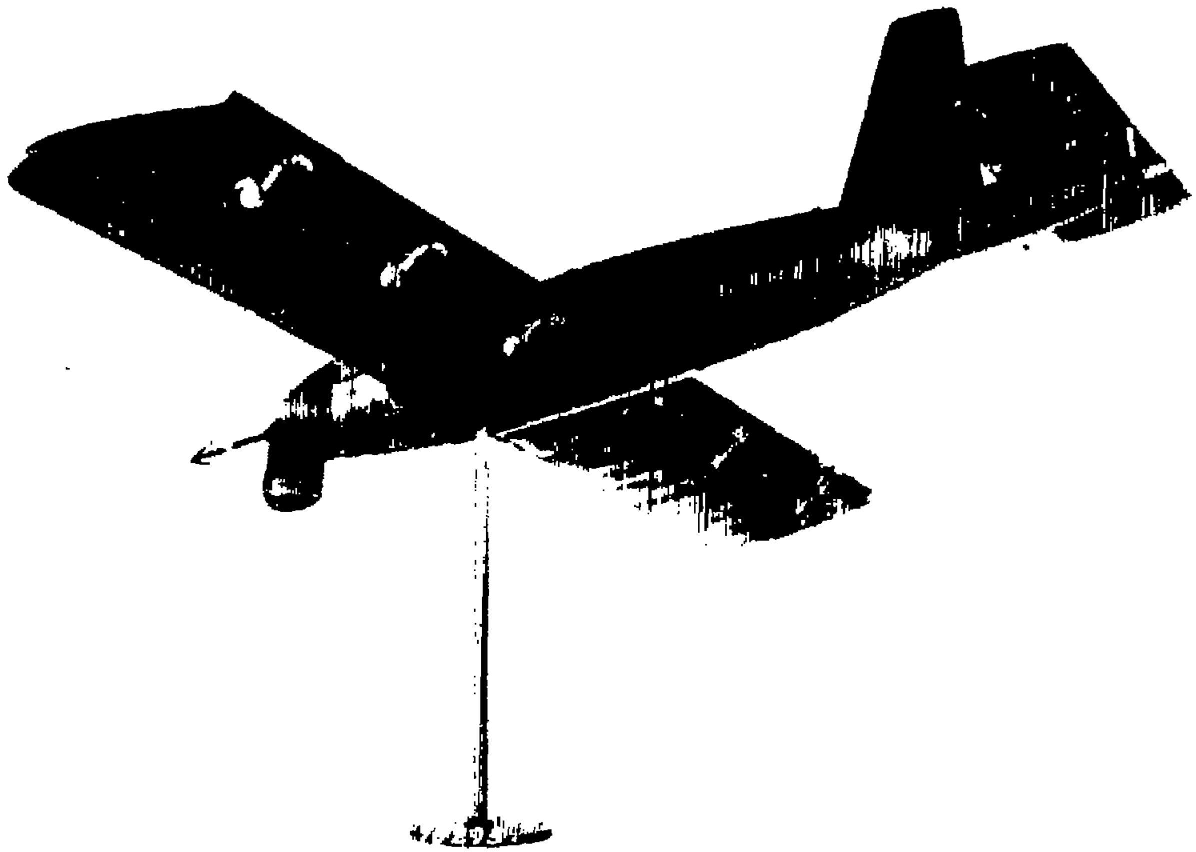


Figure 2.- Airplane model.

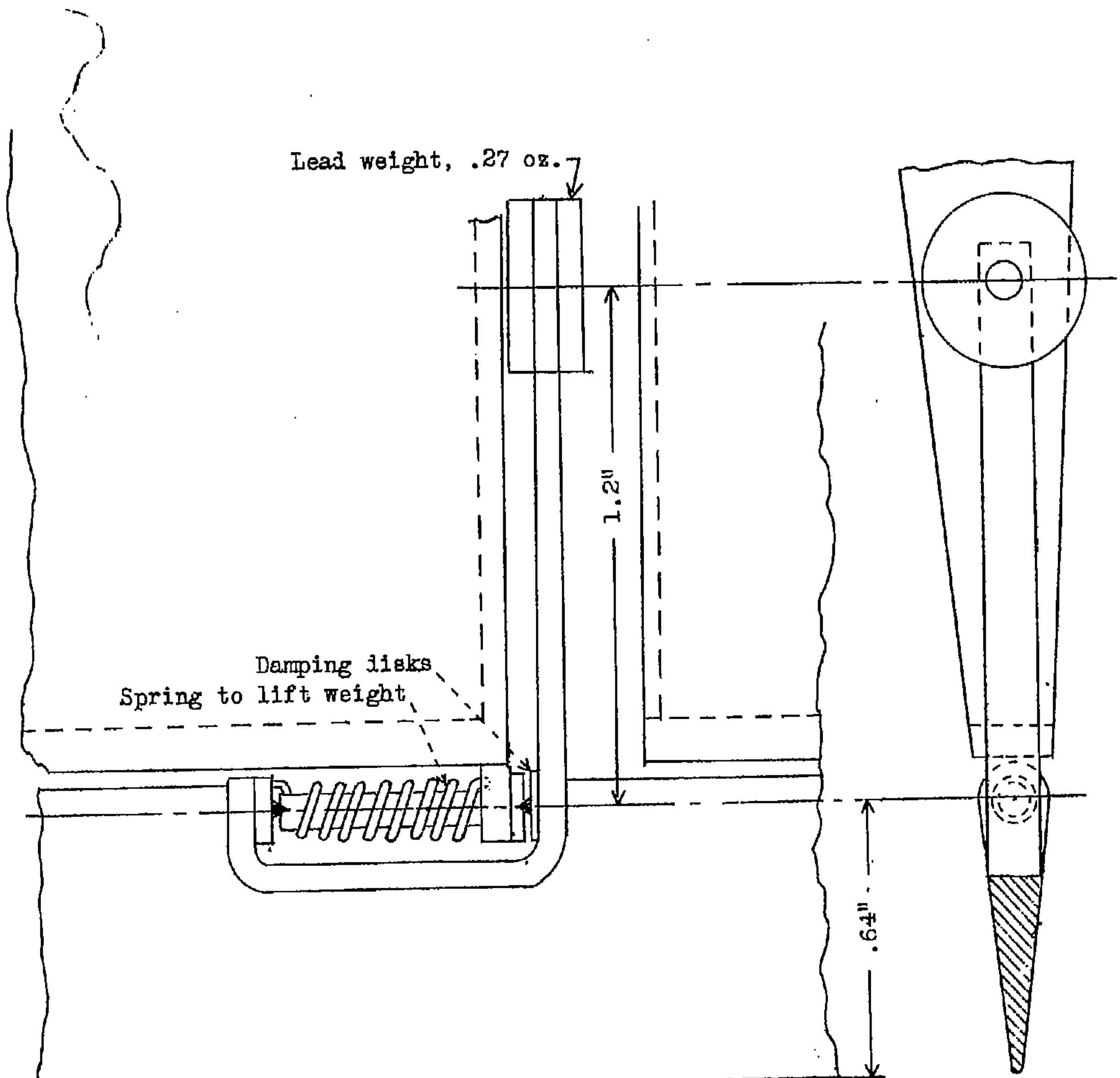


Figure 3.- Detail of flap hinge. Six hinges spaced 6 inches along span.

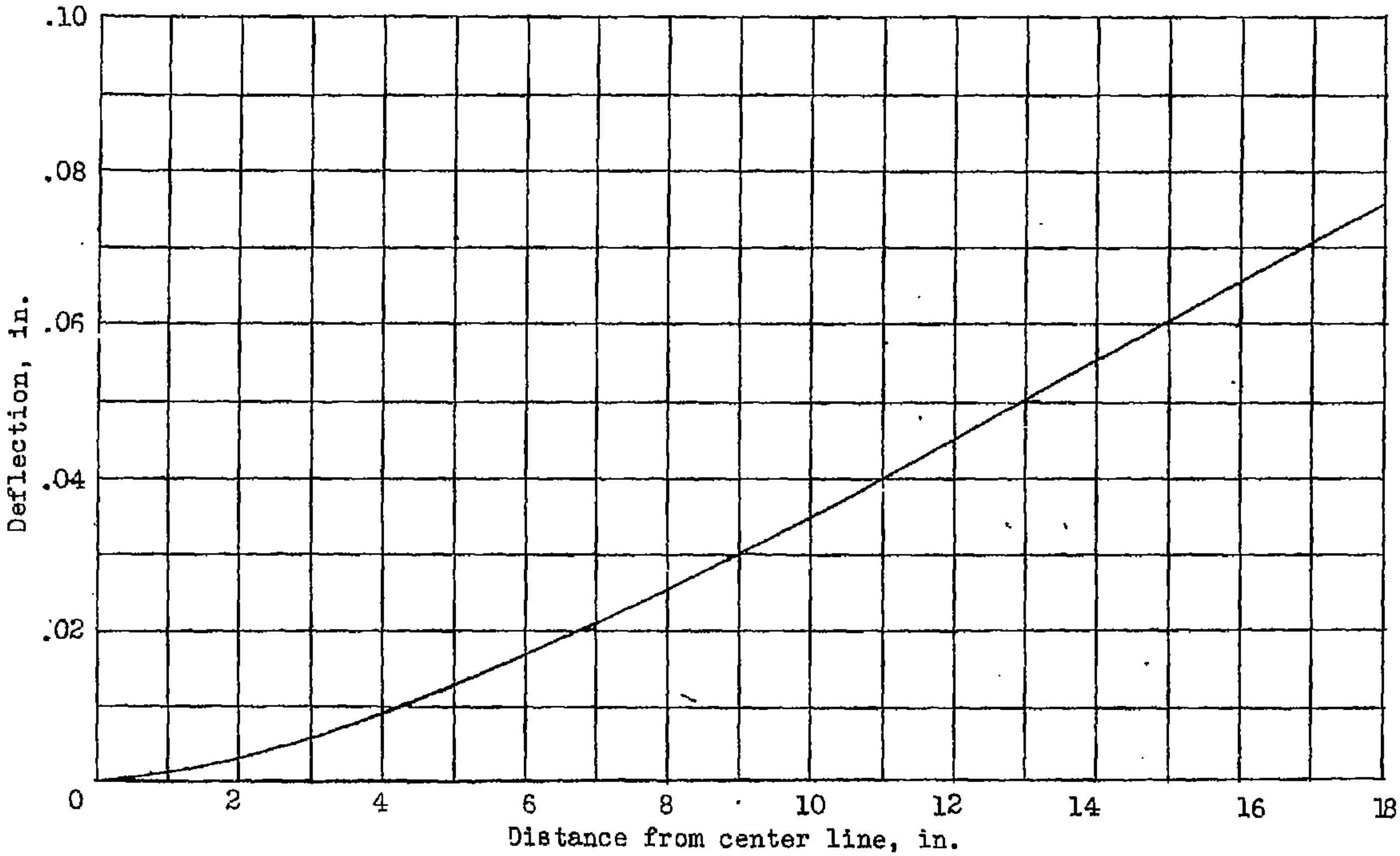
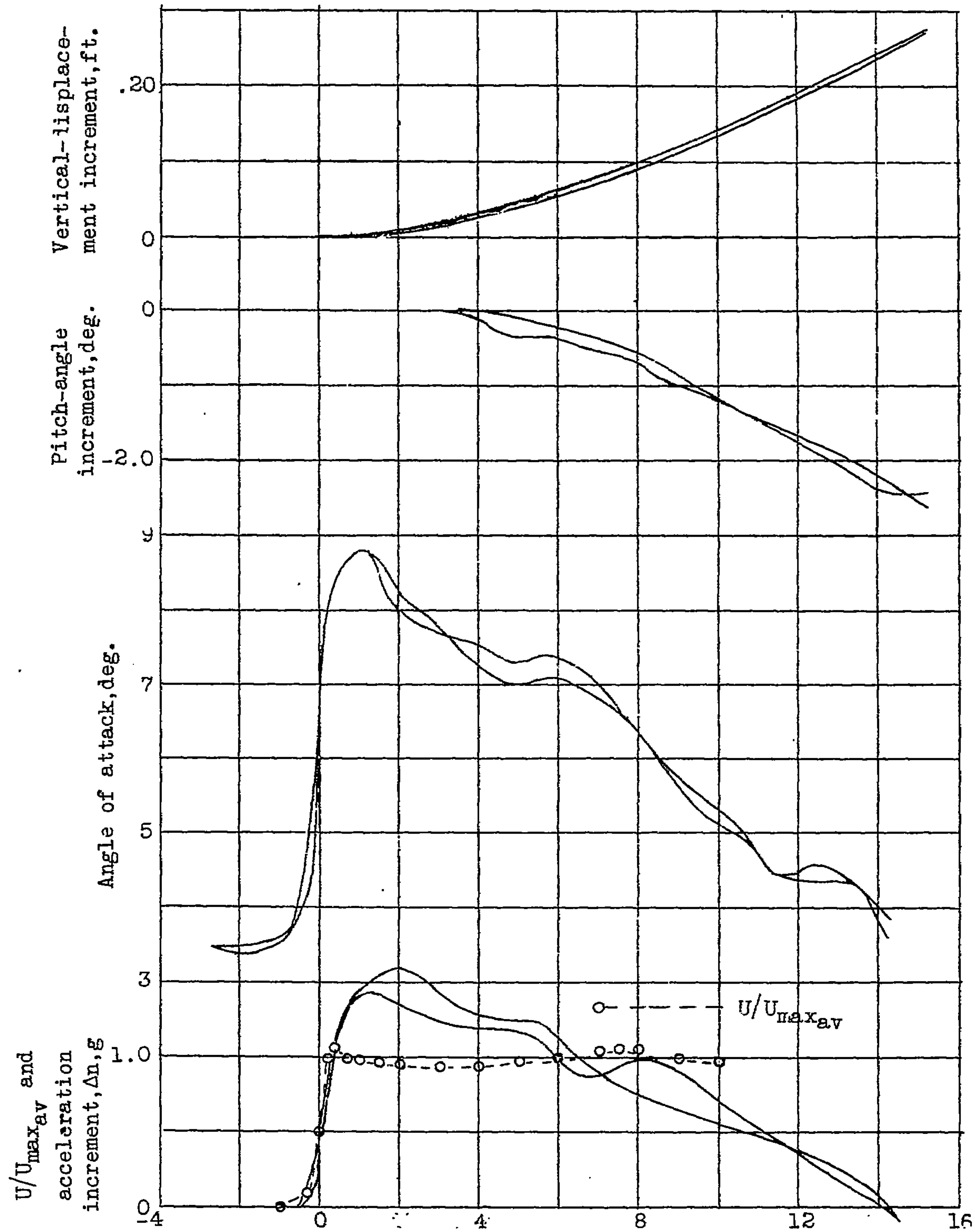


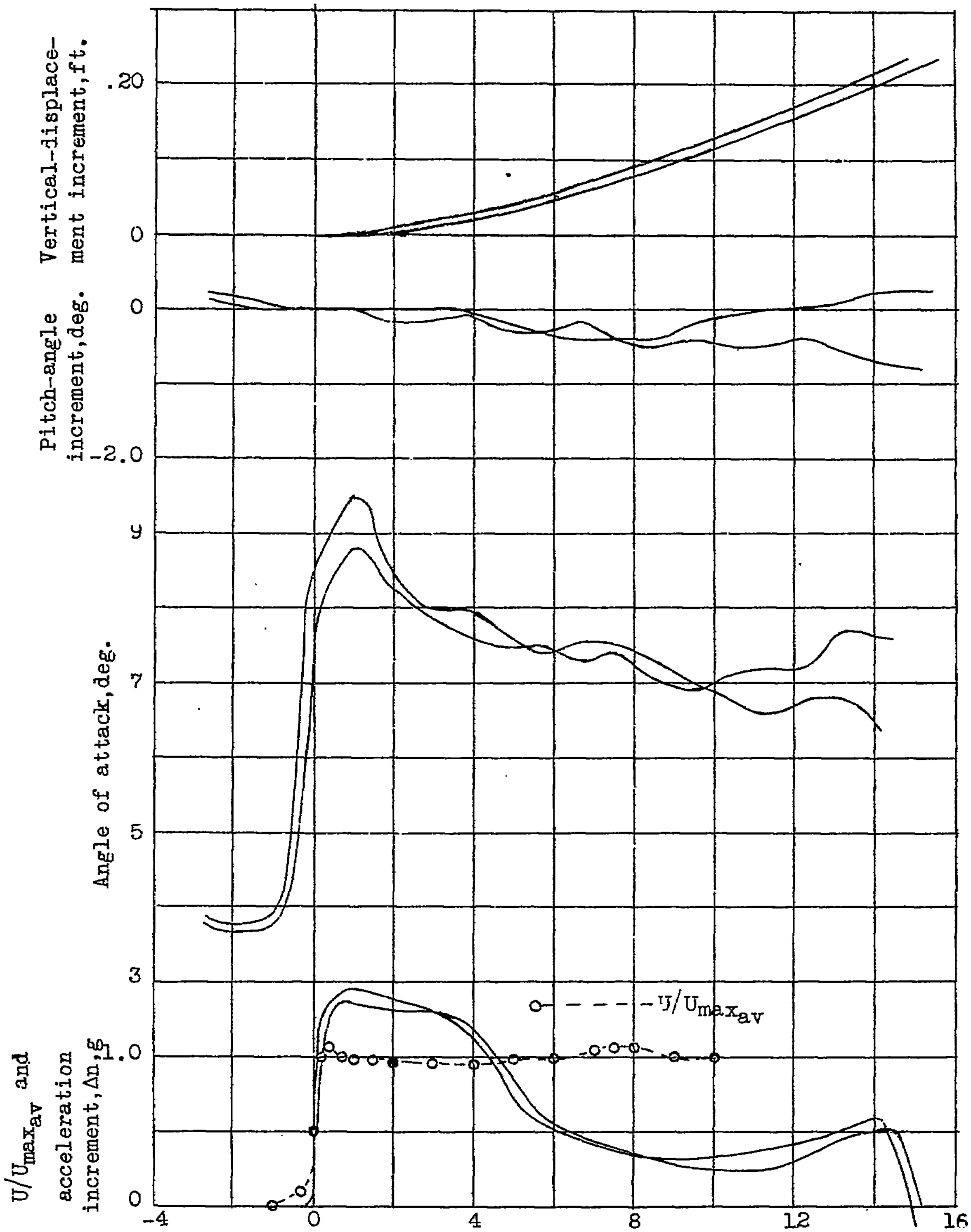
Figure 4.- Wing-deflection curve. load factor, 1.16.



Horizontal distance from leading edge of gust tunnel, chord lengths.

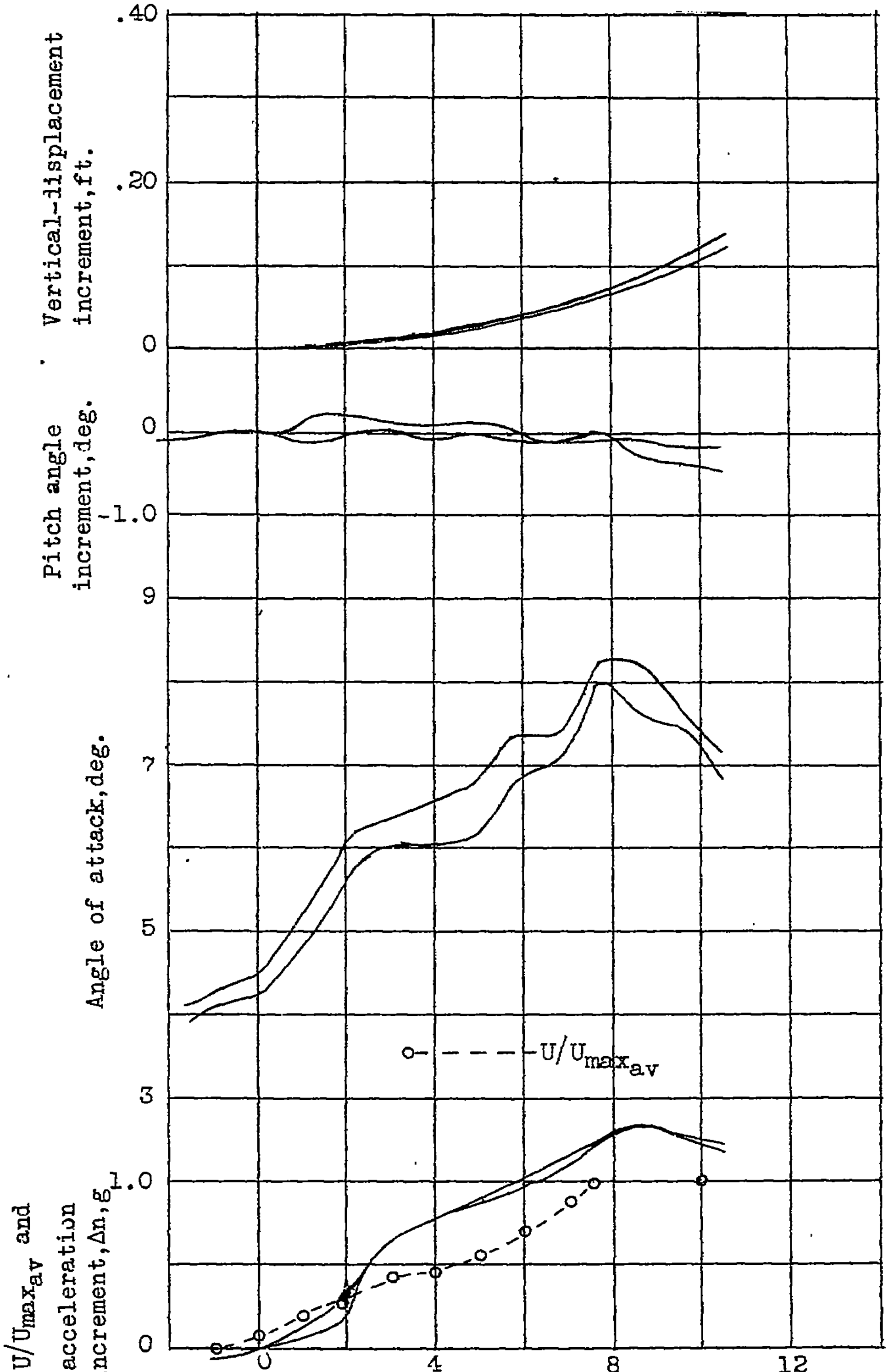
(a) Flap locked.

Figure 5a and 5b.- Histories of events in a sharp-edge gust



(b) Flap free.

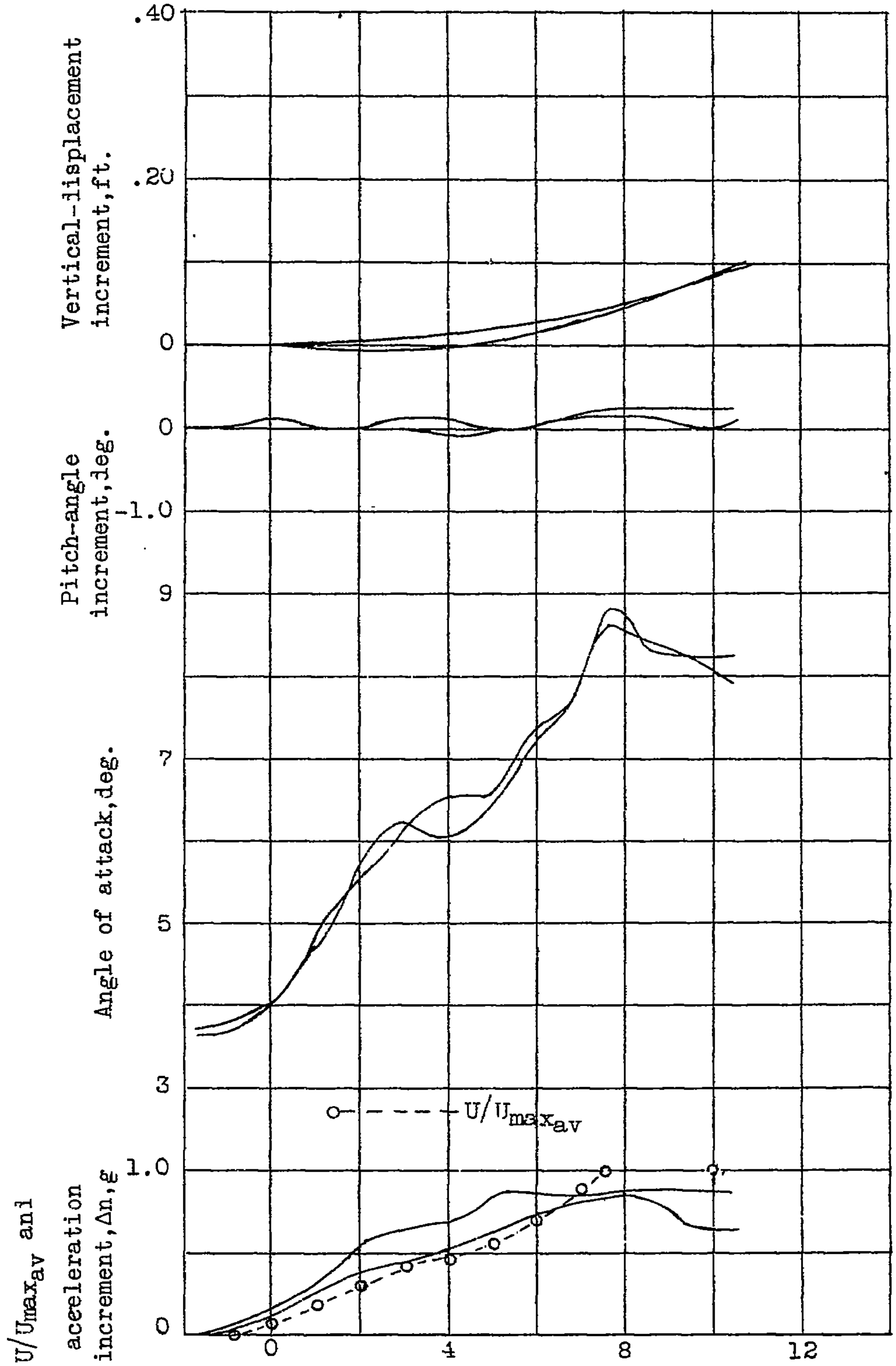
Figure 5.- Concluded.



Horizontal distance from leading edge of gust tunnel, chord lengths.

(a) Flap locked.

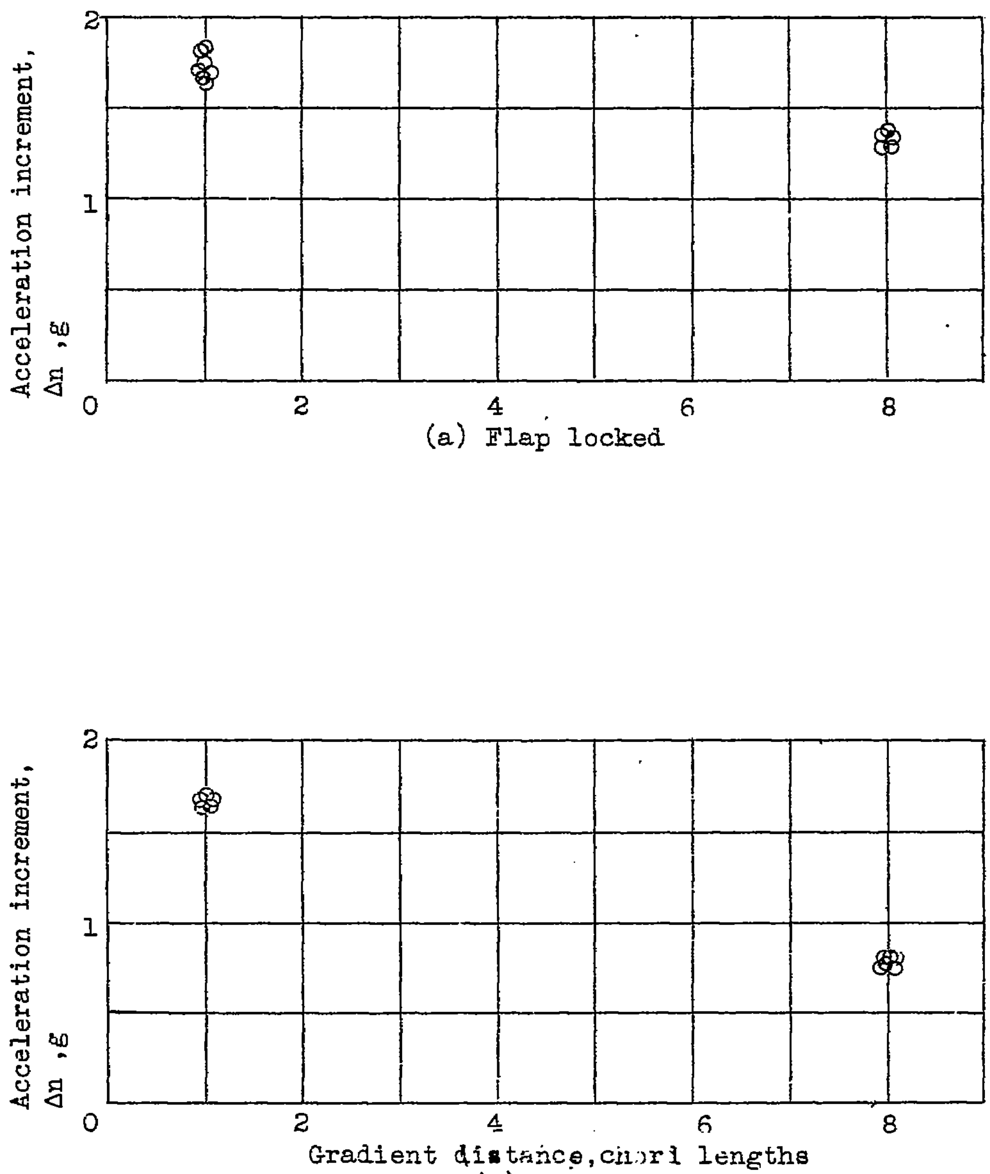
Figure 6a and b.- Histories of events in an 8-chord-length gust.



Horizontal distance from leading edge of gust tunnel, chord lengths.

(b) Flap free.

Figure 6.- Concluded.



(b) Flap free

Figure 7.- Variation of acceleration increment with gradient distance.

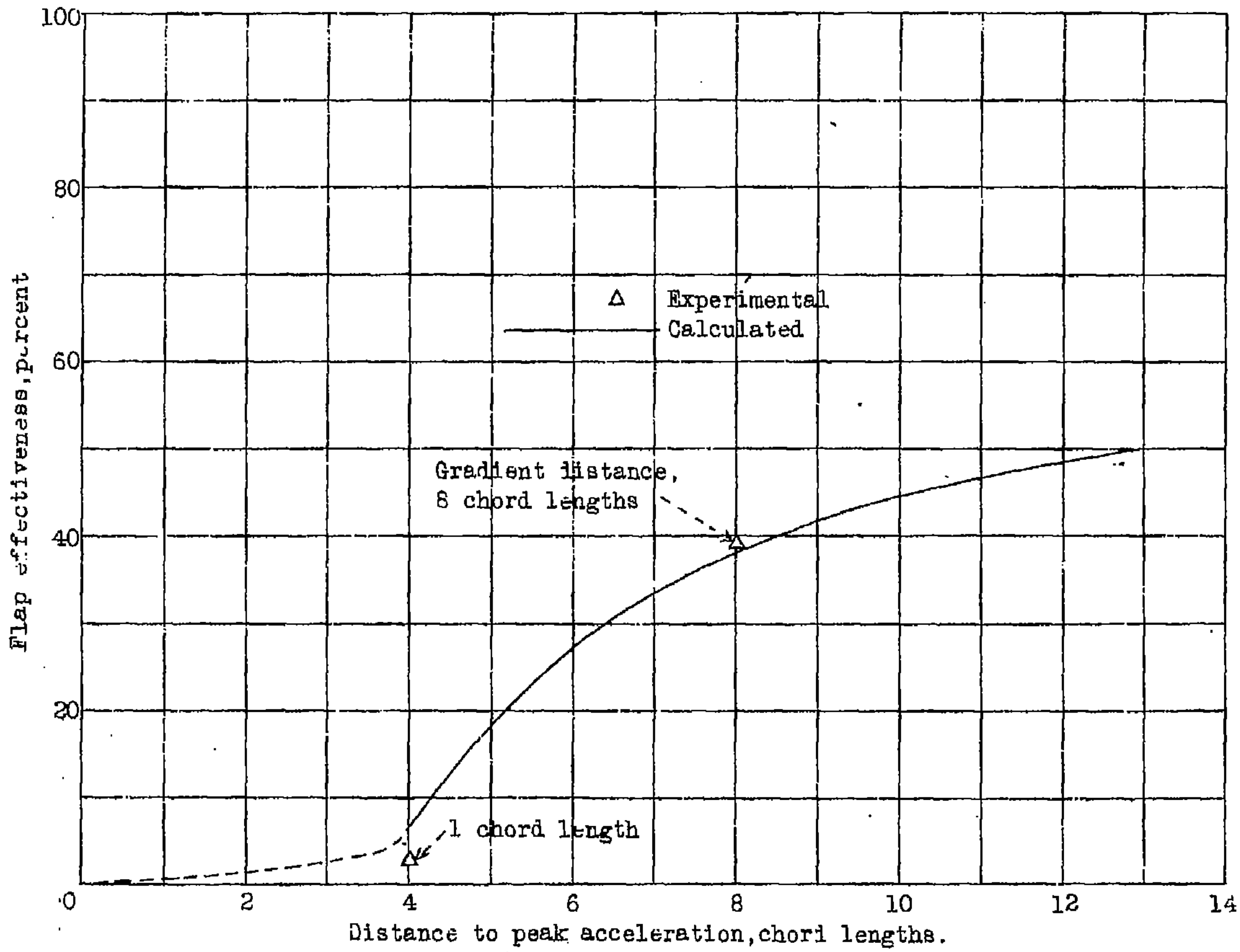


Figure 8.- Variation of flap effectiveness with distance to peak acceleration.

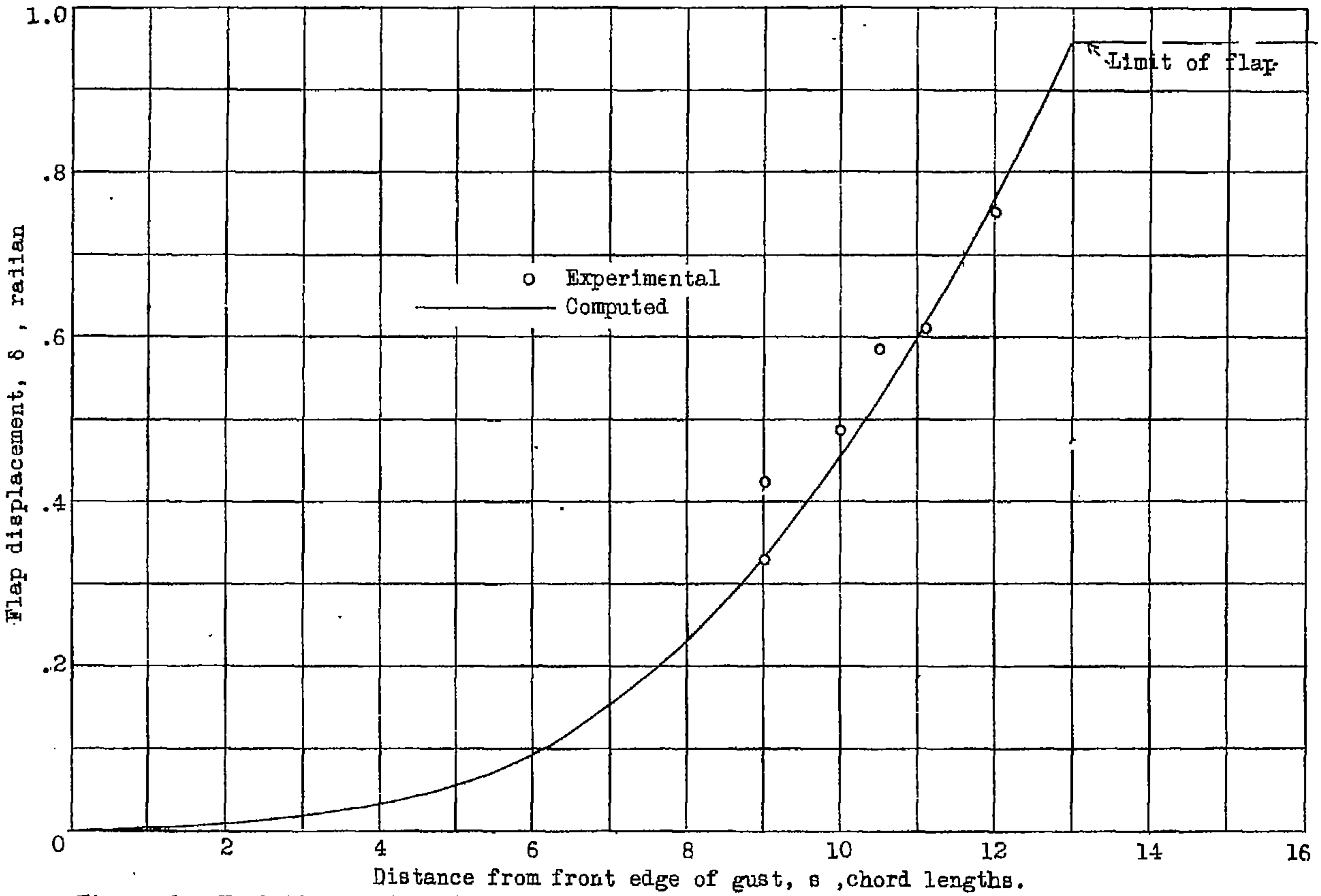


Figure 9.- Variation of flap displacement with distance penetrated into an 8-chord-length gust.

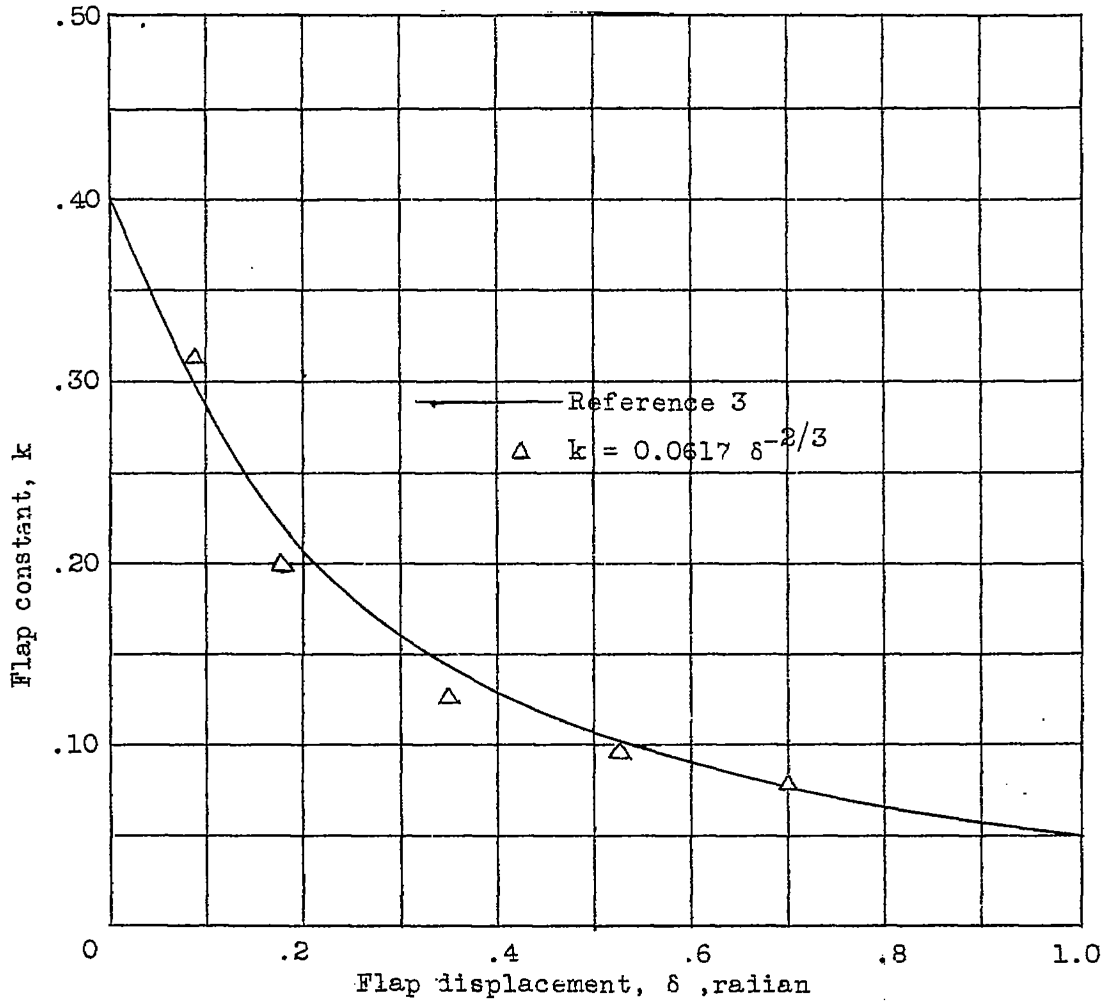


Figure 10.- Variation of flap constant with flap displacement.

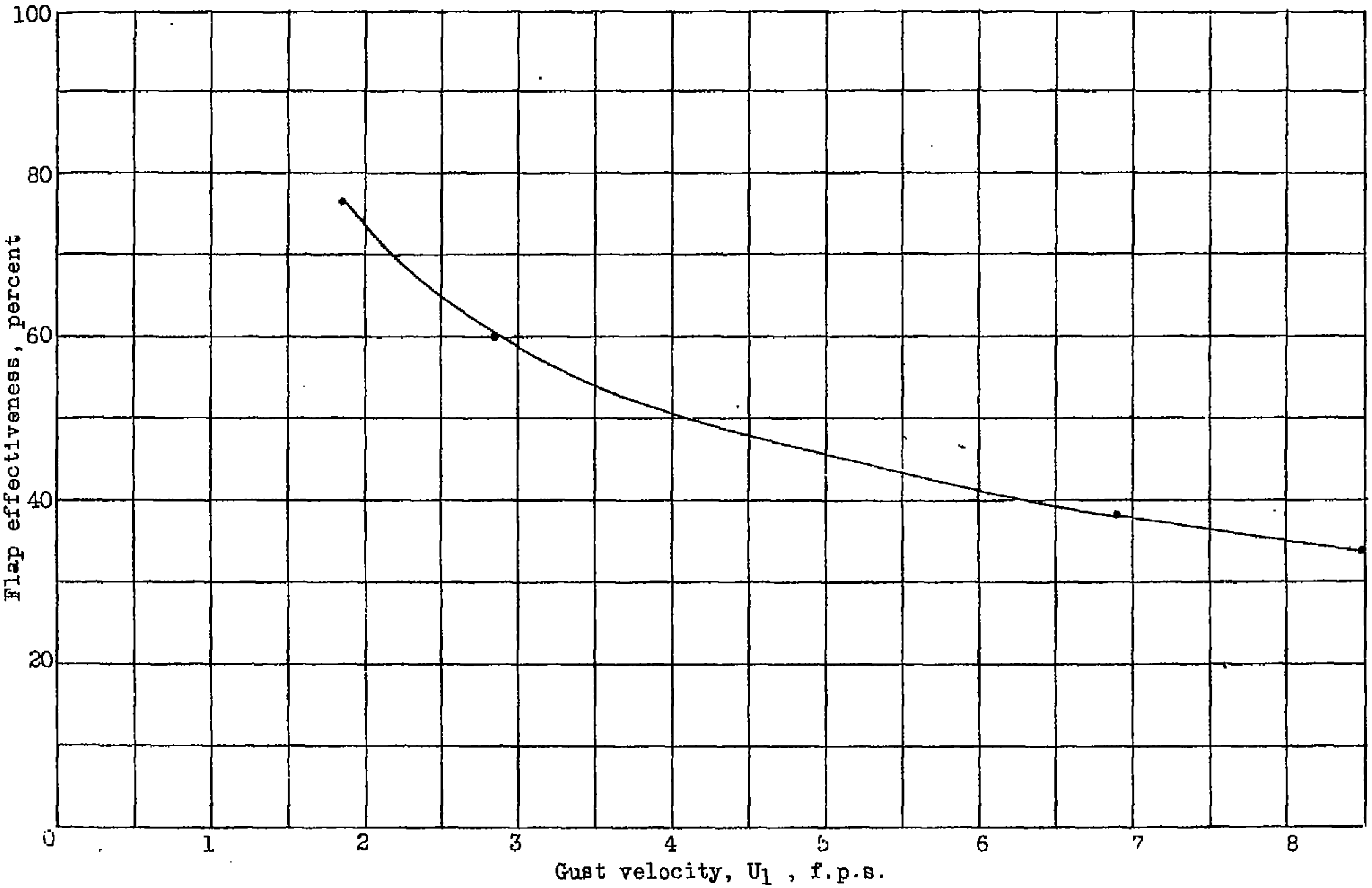


Figure 11.- Variation of flap effectiveness with gust velocity for an 8-chord-length gust.